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Risk Assessment and Maintenance of Existing Trunk Lines with a New Subsidiary System under Seismic and Deteriorating Environments

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Abstract

This paper describes a seismic risk assessment for existing trunk lines which are to be annually expanded by the subsystems consisting of a subsidiary pipeline network and the shutoff valve. The maintenance activities range from daily patrols to large-scale retrofit, while taking the deterioration effect into consideration. The discussion focuses on the probability of failure for the overall system, for various combinations of the safety level in the control valve and the pipeline network.

Keywords: Fast-tracking; contractual risks; legal problems; project delivery method.

1. Introduction

All kinds of structures in Japan are threatened by two types of earthquake; those originating from plate tectonics and those from inland active faults. Furthermore, all existing structures are in the deteriorating environments which can often significantly impair structural safety.

The existing pipelines were designed to comply with the safety requirements based on the seismic design codes prevailing at that time, and have been safely operated by performing daily maintenance. Over many years, however, the original system will face not only severe loading conditions but also many business requirements, and therefore may be expanded with subsidiary systems which consist of a pipeline network and one shutoff valve to disconnect the subsystem from the main line when a leakage or breakage occurs in the subsystem or valve equipment. It is important to note that the original system and

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future subsidiary systems were separately designed based on their own probabilities of failure; the probability of failure for a future overall system was not considered at the initial stage.

If firms require the performance of the system to be improved each year, the present system must be expanded year by year, but the overall system then has a greater risk of potential defects as well as a higher probability of failure under seismic and deteriorating environments.

In order to keep the probability of failure for the overall system below the target level, potential defects must be minimized through daily patrols and periodic inspections. Especially, when the system is located in a seismically active area, repairs and retrofitting are also necessary to keep its seismic performance at the required level.

The present study considers that when a new subsidiary system is introduced into the existing system, the current maintenance scheme should be revised to comply with a new safety requirement which is based on the probability of failure for the existing system and that for the new subsidiary one.

It should be noted that the existing system is conditioned on the fact that the system actually exists and on the annual rate of occurrence of various types of damage including corrosion defects, dents and mechanically defective cracks produced under deteriorating situations. Since the seismic damage to buried pipelines is often initiated at these deterioration- induced defects for severe ground motions and large peak ground displacements due to liquefaction and fault movements, maintenance activities should focus on these defects to ensure pipeline safety.

This paper also discusses the probability of failure for the overall system, for various combinations of the safety level of the control valve and the pipeline network in the subsidiary system. The final objective is to propose several maintenance options for the overall pipeline system under seismic and deteriorating environments.

2. Reliability analysis

2.1. Model system

A typical example of a trunk line in Japan is shown in Figure 1. The supply to meet the demand in each district is delivered through each control valve to the subsystems, which have been constructed year by year as demand has increased. The basic configuration of the pipeline system is shown in Figure 2 where many subsystems branch out along the trunk line.

Figure 3 shows the numerical model used in this study in which A is the source node and B is the demand node, and the k-th subsystem is constructed after the (k-1)-th subsystem was successfully operated.

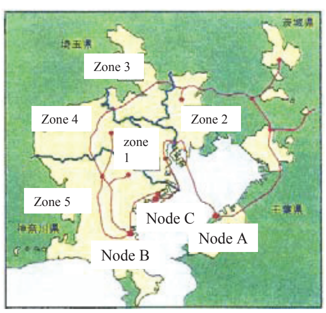


Figure 1. A typical pipeline configuration in Japan.

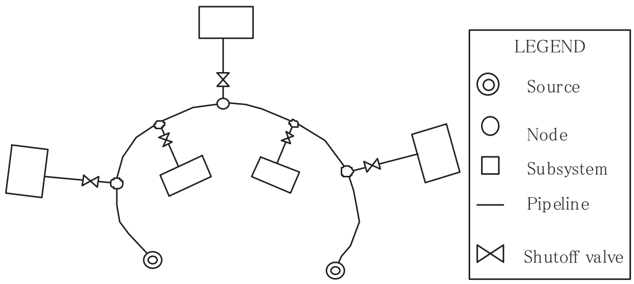


Figure 2. A simplified model of a pipeline system with several subsystems.

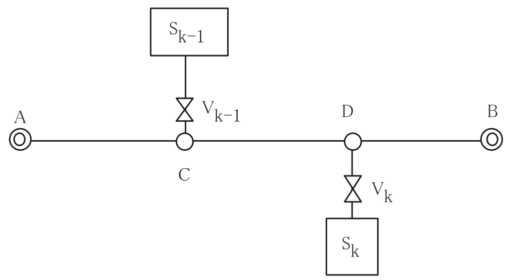


Figure 3. The numerical model of the k-th subsystem provided after the (k-1)-th subsystem which was successfully operated.

2.2.Seismic performance and damage modes

2.2.1. Definitions

Existing lifelines in Japan are always threatened by seismic hazards of Level 1 and Level 2 ground motions caused by the maximum operating earthquake (EQ1) and the maximum considered earthquake (EQ2), respectively.

(1) Definition of seismic performance

Seismic performance of a lifeline system (Imai & Koike 2009) can be defined as shown in Table 1.

Table 1. Definition of seismic performance

Seismic performance	Definition
1	The system performance can be maintained without any disruption for a Level 1 earthquake ground motion (EQ1), whether the system is slightly damaged or not.
2	The system performance can be restarted after short repair for a Level 2 earthquake ground motion (EQ2), when the system is not significantly damaged.
3	The system performance can be restored after disruption by a Level 2 earthquake ground motion (EQ2), when the system is not completely damaged.

The seismic performance can be qualitatively defined in terms of the probability of performance damage modes as follows.

(2) Definition of performance damage modes

The performance damage modes of a lifeline system are defined as shown in Table 2.

Table 2. Definition of performance damage modes

Damage mode	Definition
Minor D_{EQ}^{minor}	The system serviceability is in the minor damage state by EQ1, and the probability of minor damage occurrence is defined as $p_{D_{EQ}}^{\mathrm{minor}}$.
Moderate $D_{EQ}^{\mathrm{moderate}}$	The system serviceability is in the moderate damage state by EQ2, and the probability of moderate damage occurrence is defined as $p_{D_{EQ}}^{\mathrm{moderate}}$.
Major D_{EQ}^{major}	The system serviceability is in the major damage state by EQ2, and the probability of major damage occurrence is defined as $p_{D_{EQ}}^{\mathrm{major}}$.

The probability of performance damage modes means the probability that the seismic performance cannot be maintained in the event of seismic load EQ1 or EQ2.

(3) Definition of structural damage modes

The structural damage modes of a lifeline component are defined as shown in Table 3.

Table 3. Definition of structural damage modes

Damage modes	Definition
Minor Z^{minor}	The elastic structural response S_1^B exceeds the critical level S_a^B by EQ1, and the probability of minor damage occurrence is defined as $p_{Z_{EQ}}^{\text{minor}}$.
Moderate $Z^{moderate}$	The inelastic structural response ε_2^{B*} exceeds the critical level ε_U^B for a small leakage by EQ2, and the probability of moderate damage occurrence is defined as $p_{Z_{EQ}}^{\text{moderate}}$.
Major Z^{major}	The inelastic structural responseε_2^{B*}exceeds the critical level ε_U^B for a large leakage by EQ2, and the probability of major damage occurrence is defined as $p_{Z_{EQ}}^{\text{major}}$.

Let us define the damage modes for structural components as follows:

$$\begin{aligned} Z_{EQ}^{\text{minor}}(t,x) &\equiv R^{\text{minor}}(C_S,t)-(D+L)-S_1\cdot 1_{EQ_1} \\ Z_{EQ}^{\text{moderate}}(t,x) &\equiv R^{\text{moderate}}(C_S,t)-(D+L)-S_2\cdot 1_{EQ_2} \\ Z_{EQ}^{\text{major}}(t,x) &\equiv R^{\text{major}}(C_S,t)-(D+L)-S_2\cdot 1_{EQ_2} \end{aligned} \tag{1}$$

where Z, R, C_S, D, L, S are performance function, pipe strength, seismic disaster prevention investment, dead load, live load and seismic load, effectively, and 1_{EQ} is given by

$$1_{EQ} = \begin{cases} 1: \text{an earthquake } EQ \text{ occurs at } t \\ 0: \text{an earthquake } EQ \text{ does not occur at } t \end{cases}$$

2.2.2. Probability of performance damage modes

In the case of major damage mode, for instance, the probability of performance damage is given by:

$$\begin{aligned} p_{D_{EQ}}^{\text{major}} \equiv P\left[D_{EQ}^{\text{major}}(t)\right] = \bigcup_{x\subset L_{AB}} & P\left[D_{EQ}^{\text{major}}(t)\middle| Z^{\text{major}}(t,x)<0\right] \\ & \cdot P\left[Z^{\text{major}}(t,x)<0\middle| EQ2\right] P[EQ2] \end{aligned} \tag{2}$$

where L_{AB} is linear stretching length between nodes A and B. The strength Rmajor(CS, t) of the lifeline system can be upgraded when the seismic disaster prevention investment CS is adequately used for the retrofitting work. The probability of performance damage mode in various stages of the system can then be estimated with its corresponding resistance of the system as follows:

(1) the initial strength:

$$R^{\text{major}}(0,0) \tag{3a}$$

(2) the strength before the retrofitting:

$$R^{\text{major}}(0,T_p) = \psi(T_p)\cdot R^{\text{major}}(0,0) \tag{3b}$$

(3) the strength after the retrofitting:

$$R^{\text{major}}\left(C_S, T_p\right) \tag{3c}$$

(4)the strength in the future:

$$R^{\text{major}}\left(C_S, t\right) = \psi\left(t - T_p\right) \cdot R^{\text{major}}\left(C_S, T_p\right) \tag{3d}$$

where CS is the seismic disaster prevention investment, and Tp is the present time, and $\psi(t)$ is a deterioration factor which is defined by

$$\psi(t) = 1 - \xi_1 \cdot \left(\frac{t}{T_D}\right)^{\xi_2} \tag{4}$$

where ξ_1 and ξ_2 are deterioration parameters and T_D is the service period of the system.

2.3.Formulation of seismic safety

2.3.1. The original trunk line

The probability of failure for the original trunk line from the source node A to the demand node B in Figure 1 is given by:

$$P\left[D_k(t)\middle|EQ\right] = 1 - \exp\left[-\sum_j \int_0^{L_{AB}} \nu_j P\left[Z_{EQ}(t,x) < 0 \middle| EQ\right] dx\right] \tag{5}$$

where ν_j is the occurrence rate of the j-th defect (j=1 corrosion; j=2 dent; j=3 crack propagation), respectively. The performance function is described by:

$$Z_{AB}(t,x) \equiv \psi(t) R_0 - D(x) - L(x) - S(x) \tag{6}$$

where $R_0, \psi(t), D(x), L(x), S(x)$ are the initial strength, deterioration factor, dead load, live load and seismic load, respectively.

In the initial stage, the pipeline system is designed such that the probability of failure is less than the following value:

$$P\left[D_0\middle|EQ\right] = 1 - \exp\left[-\sum_j \int_0^{L_{AB}} \nu_j P\left[Z_{EQ}(0,x) < 0 \middle| EQ1\right] dx\right] \tag{7}$$

2.3.2. The trunk line combined with a subsystem

When a subsystem is attached to the trunk line, the damage state of the expanded system can be defined as the summation of damage states including the trunk line AB, an additional network S1, and a control valve V1 under the condition of survival of the previous system as follows:

$$P\left[D_1\middle|\overline{D}_0\right] = P\left[D_{AB} \bigcup D_{S_1} \bigcup D_{V_1} \middle| \overline{D}_{AB}\right] \tag{8}$$

The k-th expanded system is produced when a subsystem is added to the (k-1)-th expanded system. Therefore, the damage state for the k-th expanded system is expressed as:

$$D_k(t) = D_{k-1}(t) \bigcup D_{S_k}(t) \bigcup D_{V_k} \tag{9}$$

where the parameter t is defined in the range of $t \geq t_k$. The probability of failure for the k-th subsystem is given by:

$$P\left[D_{S_k}(t) \middle| EQ\right] = 1 - \exp\left[-\sum_j \int_0^{L_{S_k}} \nu_j P\left[Z_{S_k}(t,x) < 0 \middle| EQ\right] dx\right] \tag{10}$$

where the performance function for the k-th network is defined as:

$$Z_{S_k}(t,x) \equiv \psi(t - t_k) R_{S_k} - D(x) - L(x) - E(x) \tag{11}$$

Noting that a control valve is installed at the connection point with the trunk line, the probability of failure for the k-th valve is defined as:

$$P\left[D_{V_k} \middle| EQ\right] = P\left[Z_{V_k} < 0 \middle| EQ\right] \tag{12}$$

where the performance function for the k-th valve is given as:

$$Z_{V_k} = R_{V_k} - D - L - E\left(x_{V_k}\right) \tag{13}$$

where x_{V_k} is the location of the k-th valve.

The probability of failure for the k-th expanded system is defined as

$$P\left[D_k(t) \middle| EQ\right] \equiv P\left[D_k(t) \middle| \overline{D}_{k-1}(\tau)\right] \cdot P\left[\overline{D}_{k-1}(\tau) \middle| EQ\right] \tag{14}$$

for $t \geq t_k$ and $t_{k-1} \leq \tau < t_k$

where the conditional probability can be described as follows:

$$\begin{aligned} &P\left[D_k(t) \middle| \overline{D}_{k-1}(\tau)\right] = \\ &P\left[D_{k-1}(t) \bigcup D_{S_k}(t) \bigcup D_{V_k}; t \geq t_k \middle| \overline{D}_{k-1}(\tau); t_{k-1} \leq \tau < t_k\right] \end{aligned} \tag{15}$$

2.3.3. Design hazard function for the trunk line with the k-th subsystem

Note that Eq. (15) is a hazard function for the k-th expansion system. Now we introduce a design hazard function in which the probability of failure for the k-th expansion system should be less than the design value:

$$P\left[D_k \middle| \overline{D}_{k-1}\right] \leq p_H^{T_k} \tag{16}$$

Using the following definition of the subsystem with a control valve

$$D_{SV_k}(t) = D_{S_k}(t) \bigcup D_{V_k} \tag{17}$$

the hazard function given by Eq.(15) can be written as:

$$\begin{aligned} P\left[D_k(t) \middle| \overline{D}_{k-1}(\tau)\right] &= P\left[D_{k-1}(t) \bigcup D_{SV_k}(t) \middle| \overline{D}_{k-1}(\tau)\right] \\ &= P\left[D_{k-1}(t) \middle| \overline{D}_{k-1}(\tau)\right] + P\left[D_{SV_k}(t)\right] - P\left[D_{k-1}(t) \middle| \overline{D}_{k-1}(\tau)\right] \cdot P\left[D_{SV_k}(t)\right] \\ &= P\left[D_{k-1}(t) \middle| \overline{D}_{k-1}(\tau)\right] \cdot \left\{1 - P\left[D_{SV_k}(t)\right]\right\} + P\left[D_{SV_k}(t)\right] \leq p_H^{T_k} \end{aligned} \tag{18}$$

Hence, the following equation is obtained:

$$P\left[D_{k-1}(t)\middle|\overline{D}_{k-1}(\tau)\right] \leq \frac{p_H^{T_k} - P\left[D_{SV_k}(t)\right]}{1 - P\left[D_{SV_k}(t)\right]} \text{ for } t_k \leq t,\ \ t_{k-1} \leq \tau < t_k \tag{19}$$

Figure 4 shows a schematic image of the hazard function at each time section which does not exceed the target value.

In the same way, the hazard function at the (k-1)- th step is also derived as:

$$P\left[D_{k-1}(t)\middle|\overline{D}_{k-2}(\tau)\right] \leq p_H^{T_{k-1}} \text{ for } t_{k-2} \leq \tau < t_{k-1},\ t_{k-1} < t \tag{20}$$

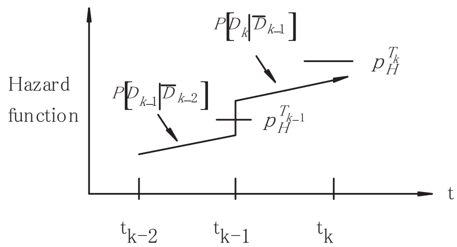


Figure 4. Profile of the hazard function at time tk-2, tk-1 and tk.

From Eq.(20), the k-th design hazard function is obtained, conditioned by the inequality formula:

$$p_H^{T_k} \geq p_H^{T_{k-1}} \cdot \left\{1 - P\left[D_{SV_k}\right]\right\} + P\left[D_{SV_k}\right] \tag{21}$$

By inverting Eq. (21), the probabilities of failure for the combined subsystem SV_k and the control valve V_k are:

$$P\left[D_{SV_k}(t)\right] \leq \frac{p_H^{T_k} - p_H^{T_{k-1}}}{1 - p_H^{T_{k-1}}} \tag{22}$$

and

$$P\left[D_{V_k}\middle|EQ\right] \leq \frac{\dfrac{p_H^{T_k} - p_H^{T_{k-1}}}{1 - p_H^{T_{k-1}}} - P\left[D_{S_k}(t)\middle|EQ\right]}{1 - P\left[D_{S_k}(t)\middle|EQ\right]} \tag{23}$$

3. Structural failure of pipeline components

3.1. Failures from potential defects under deteriorating process

Structural strength (Koike & Garciano 2005) has a time-variant characteristic due to the process of deterioration and failure will occur when the hoop stress exceeds the strength for the material having a defect X which is given by

$$R_X(t) = \psi_X(t) \cdot R_{X0} \tag{24}$$

Then the probability of failure for the material with a defect X is given by

$$p_Z^{major} = P\left[R_X^{major} - \sigma_h < 0\right] \tag{25}$$

3.1.1. Corrosion failure

The critical strength for corrosion failure is measured by the flow stress which is given by $R_{C0} = \sigma_{flow}$. The deterioration effect for the corrosion damage mode can be evaluated using the parameters:

$$\xi_{C1} = 1 - \frac{1}{M} \quad , \quad \xi_{C2} = \frac{1}{2} \tag{26}$$

where M is the Folias factor.

The hoop stress of the pipeline is applied to the defect as the load effect and is given by:

$$\sigma_h = \frac{P_r \cdot D}{2t} \tag{27}$$

where Pr , D, and t are the internal pressure, diameter and wall thickness of the pipeline, respectively.

3.1.2. Dent failure

The critical strength of a dent defect with a gouge as shown in Figure 5 is formulated by:

$$R_{D0} = \sigma_{flow} \frac{2}{\pi} \cos^{-1}(s) \tag{28}$$

$$\text{where, } s = \exp\left[-\frac{1.5\pi E}{\sigma_{flow}^2 Ad} \cdot \frac{\exp\left\{\dfrac{\ln C_v - K_1}{K_2}\right\}}{\left\{Y_1\left(1 - \dfrac{1.8L_d}{2R}\right) + Y_2\left(10.2\dfrac{L_d}{2t}\right)\right\}^2} \right]$$

$$Y_1 = 1.12 - 0.23\left(\frac{d}{t}\right) + 10.6\left(\frac{d}{t}\right)^2 - 21.7\left(\frac{d}{t}\right)^3 + 30.4\left(\frac{d}{t}\right)^4$$

$$Y_2 = 1.12 - 1.39\left(\frac{d}{t}\right) + 7.32\left(\frac{d}{t}\right)^2 - 13.1\left(\frac{d}{t}\right)^3 + 14.0\left(\frac{d}{t}\right)^4 \tag{29}$$

Then the corresponding dent is also given by

$$L_d(t) = \left(\frac{t}{T_D}\right)^{\xi_{D2}} L_{d\max} \tag{30}$$

where L_{dmax}, t and TD are the maximum dent size, time and service period of the system, respectively.

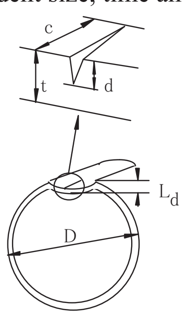


Figure 5. A schematic profile of a dent with a gouge.

3.1.3. Crack propagation

Conventional analytical methods use the following formula to estimate the critical strength for crack propagation:

$$R_{P0} = \left\{ \frac{C_V}{f(R,t)} \right\}^{1/\eta} \tag{31}$$

where $C_v, f(R,t)$ and η are Charpy toughness, a coefficient formula assigned by each design code with pipe parameters of radius R and wall thickness t, and a parameter for crack propagation, respectively.

For instance, AISI recommends the following formula as the critical strength:

$$R_{P0} = \left\{ \frac{C_V}{1.5 \times 2.377 \times 10^{-4} (Rt)^{1/2}} \right\}^{2/3} \tag{32}$$

3.2. Failures due to seismic loads

The probability of failure due to a seismic effect is evaluated by different formulations which depend on the earthquake load type produced by the ground response of the surface ground or permanent ground displacement (PGD).

3.2.1. Seismic wave effect

When a seismic wave effect is given by the ground response, the following formula gives the probability of failure for earthquakes EQ1 and EQ2, respectively:

$$P\left[\varepsilon_{cr} < \varepsilon_S \middle| EQ_i\right] \tag{33}$$

where ε_{cr} is critical strain, and ε_S is seismic strain produced in the pipeline given by:

$$\varepsilon_S = q\alpha_S\varepsilon_G \tag{34}$$

where q, α_S and ε_G are slippage factor, conversion factor and the ground strain, respectively. Each of these parameters is given by:

$$q = 1 - \cos\xi + \left(\frac{\pi}{2} - \xi\right)\sin\xi \quad , \quad \xi = \arcsin\left(\frac{\tau_{cr}}{\tau_G}\right)$$

$$\alpha = \frac{1}{1 + \left(\frac{2\pi}{\lambda \cdot L}\right)^2} \quad , \quad \lambda = \sqrt{\frac{K_1}{EA}} \tag{35}$$

$$\varepsilon_G = \frac{2\pi}{L} U_h$$

where $\tau_{cr}, \tau_G, K_1, E, A, L$ and U_h are critical shear strain, shear strain at the pipe surface, spring modulus, Young's modulus, cross-sectional area of the pipe, apparent wavelength and free field displacement which is given by:

$$U_h = \frac{2}{\pi^2} S_{V_i}(T) \cdot T \tag{36}$$

where S_V and T are the response velocity spectrum and the typical period of the surface ground, respectively.

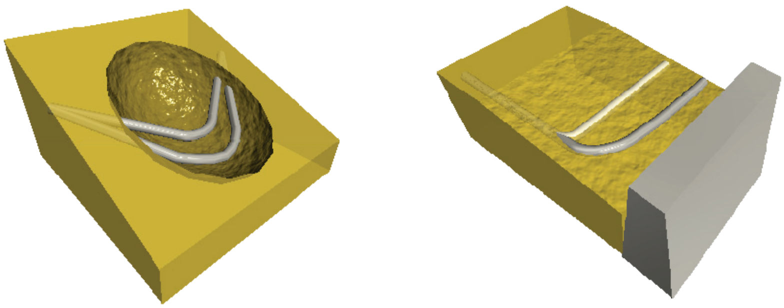
3.2.2. Peak ground displacement in a liquefied zone

The Japan Gas Association (JGA 2000) described the seismic assessment method for a pipeline crossing a liquefied zone in which the peak ground displacement (PGD) produces an opening or closing angle at a bend pipe as shown in Figure 6.

Noting that failure occurs when the deformed angle exceeds the critical value, the probability of failure is given by:

$$P\left[\omega_{cr} < \omega_L \middle| EQ_i\right] \tag{37}$$

where ω_L, ω_{cr} are deformed angle and its critical value.



(1) On a slope (2) Along a quay wall

Figure 6. Schematic profiles of liquefaction damage of bend pipes on a slope and along a quay wall.

For instance, for a bend pipe located in a liquefied slope area, and which is deformed in the opening mode, the JGA proposed the following formula:

$$\omega_L = \frac{150\delta_h}{L_{po1}}\left(0.49\frac{D}{D_{600}} + 0.69\right) \tag{38}$$

$$\omega_{cr} = 2.24\frac{\phi}{\sqrt{\frac{D}{t_b}} \cdot \left(\frac{R_c}{D}\right)^{0.25}\eta} \tag{39}$$

where,

$$L_{po1} = \sqrt{\frac{1200EI\delta_h}{P_1}}, \; P_1 = D\sigma_{flow} \tag{40}$$

and $\delta_h, D_{600}, R_c, \eta$ are permanent ground displacement, pipe diameter of 600mm for calibration purposes, radius of curvature of the bend pipe, and a parameter ranging from 0.77 to 0.88.

4. Maintenance managements for trunk line with sub-systems

4.1. Maintenance strategies

When a pipeline system is developed by adding a new subsystem to the trunk line, the maintenance engineer should consider the following four items in the maintenance strategy:

(1) A failure spreading from the subsystem to the trunk line must be stopped at the shutoff valve. Therefore, a high-quality control valve should be installed.
(2) Special attention should be paid to the deteriorated portions in the preceding subsystems.
(3) Daily patrol and periodic inspections should be carried out to maintain the safety for the serviceability limit state; and
(4) A large-scale retrofitting project should be prepared to ensure the safety for the ultimate limit state.

4.2. Daily maintenance and large-scale retrofitting

4.2.1. Field patrols and visual inspections

Field patrols are effective to avoid dent accidents caused by third-party incidents. Visual inspections are useful to detect corrosion cracks and any other evidence of deterioration before a disaster occurs. These maintenance activities can minimize the increase of potential defects. In the present study, statistical data of potential cracks are assumed as shown in Table 4.

Table 4. Statistics values of defect size for potential defects.

	Defect mode	Symbol	Defect size	
			mean	cov
			mm	
1	Corrosion crack	*C*	10	0.3
2	Dent	*D*	20	0.3
3	Crack propagation	*P*	5	0.3

In order to decrease these potential defects, however, full-scale inspection and retrofitting must be executed.

Figure 7 shows a schematic profile of the inspection filter for full-scale inspections, in which the maximum and minimum bounds for crack detection is assumed in Table 5 are as shown in Table 5.

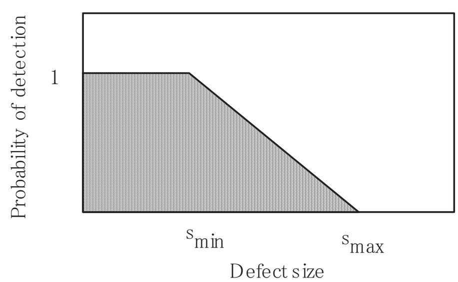


Figure 7. Schematic profile of the inspection filter.

Table 5. The bounds of defect size for the inspection

Symbol	Unit	Value
s_{min}	mm	5
s_{max}	mm	15

In large-scale retrofitting, detected defects must be automatically repaired, and the defective material must be immediately replaced with new material. This updating process, as shown in Figure 8, is assumed to be carried out by the Bayesian approach (Ang & Tang 1975)in which the revised distribution is given by:

$$f_S^*(s) = \frac{P\left[\overline{\text{detection}}\middle|s\right] f_S(s)}{\int P\left[\overline{\text{detection}}\middle|s\right] f_S(s)\,ds} \tag{41}$$

where $f_S, f_S^*, P\left[\overline{\text{detection}}\middle|s\right]$ are prior distribution, posterior distribution and probability of the non-detection, respectively.

Then the probability of failure for a pipe element having a potential defect is given by

$$P\left[Z_{EQ}(t,x) < 0 \middle| EQ\right] = \int_S P\left[Z_{EQ}(t,x) < 0 \middle| S = s, EQ\right] f_S^*(s)\,ds \tag{42}$$

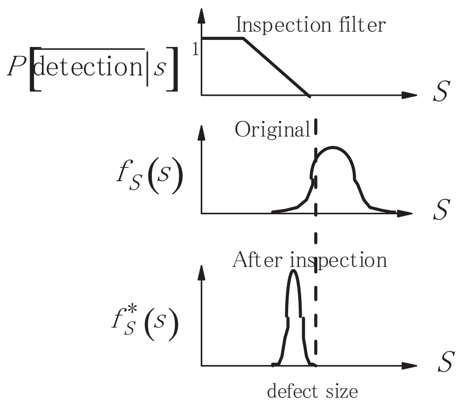


Figure 8. Probability density functions of defect size in the inspection filter, before inspection and after inspection.

4.3. Simulated results for optimal maintenance management

For the numerical calculations, the following three items are considered:

(1) large-scale retrofitting;

(2) target level of design hazard functions;

(3) quality assurance of control valves.

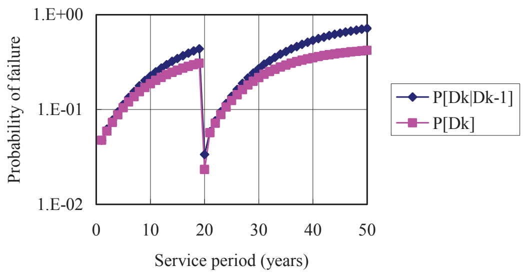
The effects of deterioration on potential defects are taken into account by deterioration parameters as shown in Table 6.

Table 6. Deterioration parameters of potential defects

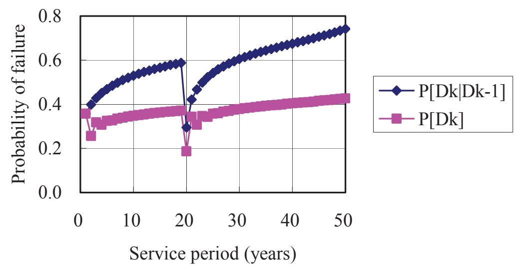
			Deterioration parameters		Duration year
	Defect mode	Symbol	ξ_1	ξ_2	T_D
1	Corrosion crack	C	0.5	0.5	50
2	Dent	D	0.75	0.5	50
3	Crack propagation	P	1	0.5	50

4.3.1. *Effect of large-scale retrofitting activity*

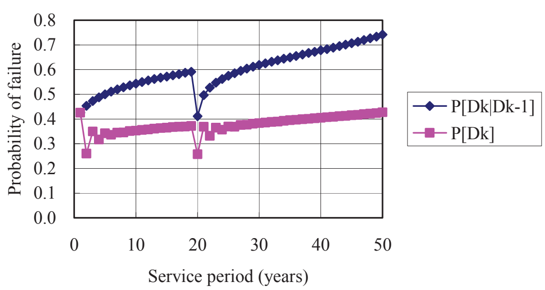
Large-scale retrofitting is carried out 20 years after the starting point. Figure 9 shows three different profiles of Eq. (18) for the earthquake load conditions of EQ1, EQ2 and EQ2+PGD, respectively. The ordinate of these figures is the hazard function, $P[D_k|D_{k-1}]$, and the probability of failure, $P[D_k]$, for the expanded system. The result for EQ1 and EQ2 are similar, but the case of EQ2+PGD shows a simple curve before and after the large-scale retrofitting activity. This simple curve may be due to a comparatively large strain of seismic load which diminishes certain variations in the deterioration effect and revised distribution by the Bayesian approach.



(1) EQ1



(2) EQ2



(3) EQ2+PGD

Figure 9. Effect of large-scale retrofitting for various earthquake load combinations.

4.3.2. *Target level of design hazard functions*

In order to obtain an appropriate probability of failure for the expansion system, the hazard function in Eq.(15) must be controlled to be less than the target hazard curve as shown in Eq.(16).

Figure 10 shows sample profiles of target hazard functions for EQ1, EQ2 and EQ2+PGD, while Figure 11 expresses the result for each earthquake load. These figures show the probability of failure for $P[D_{SV_k}]$, $P[D_{V_k}]$ and their corresponding upper bounds $P[D_{SV_k} - t]$, $P[D_{V_k} - t]$ given by Eq. (22) and (23). All these figures suggest that $P[D_{SV_k}]$ after the large-scale retrofitting shows a slightly decreasing trend. This means that retrofitting effectively improves the distribution function of residual potential defects, because the deterioration effect is increased in the model of Eq.(4).

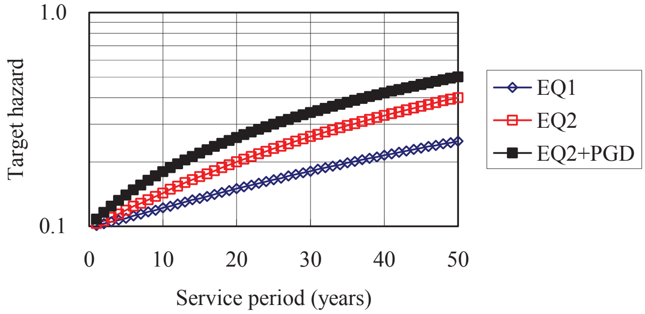
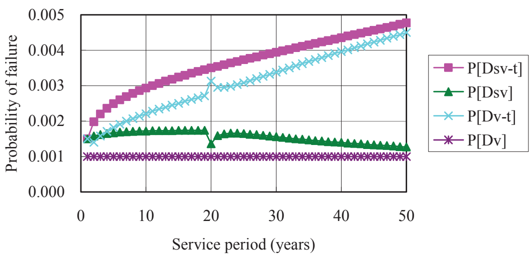
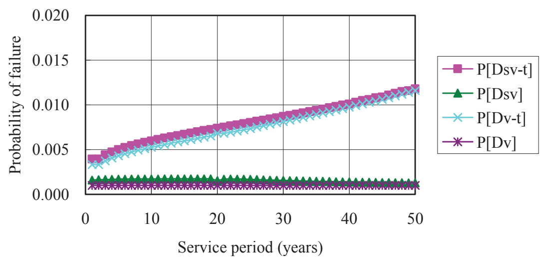


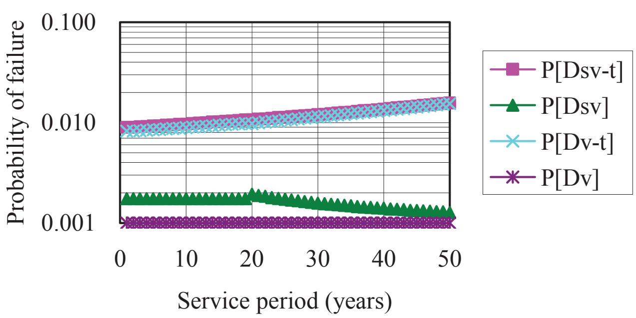
Figure 10. Target hazard function for various seismic load combinations.



(1) EQ1



(2) EQ2



(3) EQ2+PGD

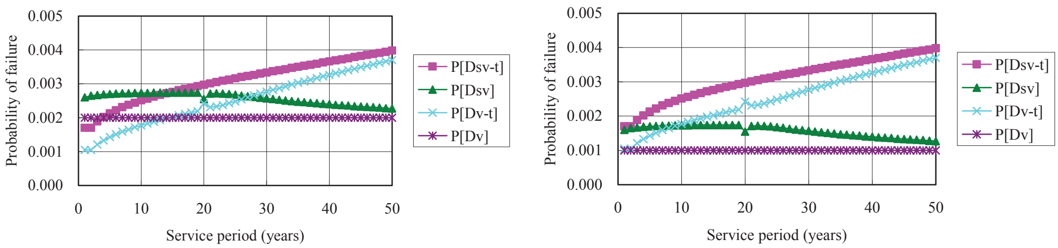
Figure 11. Assessment of the subsystem for assumed design hazard functions for seismic loads.

4.3.3. Quality assurance of control valves

The control valve is the key device for isolating the trunk line from the damaged subsystem. Therefore, the control valve must perform flawlessly in the emergency situations.

Figure 11 compares two different qualities of valve. $P[D_V] = 0.002$ means that the quality of this valve is less than that of $P[D_V] = 0.001$.

Valve (1) cannot satisfy the safety condition up to the 15th year, while valve (2) can maintain safety over the service period. This result suggests that the probability of failure for the control valve should be at least less than 0.001.



(1) P[Dv]=0.002 (2) P[Dv]=0.001

Figure 12. Required assurance quality of control valves.

5. Conclusions

Procedures for assessing the risk of expanding the trunk line by subsystems were proposed, taking into consideration the seismic and deteriorating hazards.

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